A STUDY OF INTERNATIONAL TRENDS IN METALS TECHNOLOGY AND MARKETS

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EXECUTIVE SUMMARY

According to the terms of the contract, a paper was prepared on the subject of future markets for metals and presented at a symposium at the Annual General Meeting of the Canadian Institute of Mining and Metallurgy in Ottawa on 8 May 1990. Also, a keynote presentation was made at a workshop on metal matrix composites held at the Metals Technology Laboratories of CANMET on 9 May.

A paper entitled "Metal Matrix Composites - An Overview" with an extensive appendix on "Real Components in MMC's" was prepared as a resource document for the workshop, and forms the main body of the final report.

RESUME EXECUTIF

Conformément aux termes du contrat, on a préparé un rapport sur le sujet des marchés futurs pour les métaux et on l'a présenté à l'occasion d'un colloque au réunion annuel général de l'ICMM à Ottawa le 8 mai 1990. Aussi, on a livré une présentation clef à un atelier sur les composites de matrices métalliques convoqué aux Laboratoires de Technologie de Métaux de CANMET le 9 mai.

On a préparé un rapport "Metal Matrix Composites - An Overview" avec une annexe substantive sur "Real Components in MMC's" comme document de base pour l'atelier, et ceci comprend la partie majeure du rapport final.

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METAL MATRIX COMPOSITES - AN OVERVIEW

by

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Abstract

Metal matrix composites have few actual uses. The promise of them is considered under three heads. Metal matrices at low temperatures, high temperature metallic matrices and laminar structures.

TABLE I LISTS IN MATRIX FORM composite materials which have been seriously experimented upon or are in use.

The table is schematic in form and the choice of columns and matrix are explained in the caption. The well commercialised composite materials among the examples listed are outlined in boxes. The vast majority of boxes occur with polymer matrices and/or with polymer or glass fibres. Composites containing metal fibres occur but only one example of a metal matrix. There is a good deal of promise and excitement however.

Table I

MATRIX \ FIBRE	Metal	Ceramic	Cement	Glass	Elastomer	Polymer
Metal	W / Cu; Steel / Al; W / Ni (nimonic)	WC / Co; B; SiC / Al, Ti		SiO_2 SiO_2 / Al Cu		Kevlar -or- Al; ARMOUR?
Ceramic	Mo / Al_2O_3	SiC / Cordierite; SiC C / SiC C		Glass resin + Al_2O_3 or B_4C; ARMOUR		Aramid / Glass; Aramid Al_2O_3 / Optical Fibre; BODY / ARMOUR; Roof Tiles
Cement	Steel / Portland	Asbestos / Cement; C cem; Al_2O_3 cem		Glass / High Al cem; Cemfil / Portland		Nylon / Nylon; Polyprop / Polyprop; Kevlar / Kevlar
Glass	Chicken netting / Window glass	SiC / LAS; C / Borosil		LAMINATED GLASS		LAMINATED GLASS?
Elastomer	Steel / Isoprene; TIRE / BELTING	C / Isoprene; Asbestos GASKETS Neoprene NBR		E Glass / Isoprene; TIRE		Nylon, Polyes. Aramid Isoprene BELTING TIRE
Polymer	Steel / Phenolic; BRAKES; Cu / Peel; Cu / PVC; ELEC. INS.	C / Epoxy; C / Peek; Asbestos / Phenolic; FRICTION PRODUCTS		GRP; E glass / Epoxy; PCBs; Glass / Phenolic; FRICTION PRODUCTS	Isoprene Butadiene Epoxy Styrene TOUGHENED PLASTICS	Aramid / Polyes. Phenol.; BODY ARMOUR; Aramid / Epoxy; Phenolic Phenolic FRICTION PRODUCTS; Polyester or Nylon GEO-TEXTILES / PVC film

TABLE: COMPOSITE MATERIALS SERIOUSLY EXPERIMENTED UPON OR IN USE

The table is arranged so that the columns refer to the fibre within the composite and the rows to the matrix. Thus W / Cu means a tungsten fibre in a copper matrix. The "fibre" is not always strictly fibrous in form eg it could be a plate.

Hybrids are not considered. Well commercialised materials are outlined in boxes. Cements and Elastomers are almost exclusively used as matrices but this may change. Some gaps arise due to fabrication difficulties, eg an elastomer or polymer could well improve a ceramic as far as impact resistance is concerned, but this does not occur because ceramics are fabricated at high temperature.

METAL MATRICES AT LOW TEMPERATURE

Metal-matrix composites have recently been reviewed by Chou et al (1) and by Feest (2). So far as reinforced fibrous composites for aerospace are concerned, the interest in a metallic matrix centres on the use of lower density metals and the avoidance of the disadvantages of a matrix based on a thermosetting resin. Epoxy and similar resins possess low thermal conductivity, and a high thermal expansion coefficient. They show dimensional instability, hygrothermal degradation, material loss in high vacua and are susceptible to radiation damage and embrittlement at low temperatures. The lighter metals do not possess these disadvantages.

Many metal matrix systems involving reinforcing fibres have been explored including Be, B, C, silicon carbide and alumina (of various types) fibres in Al as well as B, SiC, Be and W in Ti, and B in Mg. Reinforcement of the light metals Al or Mg is occurring in many cases in order to reduce wear or reduce creep, for example ICI Saffil in Al alloys. Squeeze casting is often the method of introduction employed. The density of Al reinforced with 50-60 vol. % of continuous Al_2O_3 fibres is only some 40% of that of steel but the tensile strength and stiffness in the fibre direction can be the same (Table 2). The fatigue strength in the fibre direction is similar to the value for steel and so such a composite has been produced to make connecting rods in the Toyota experimental FX-1 engine.

When wear, stiffness (as distinct from very high strength), controlled thermal expansion and/or moderate increases in temperature of service are the aim, it is often not necessary to use fibres. Fibres are usually expensive to make compared with other forms of inherently strong solids. By methods based on powder metallurgy very (comparatively) cheap forms of B_4C, SiC and other strong solids can be introduced into aluminium, magnesium and copper matrices. Volume fractions as high as 40% can be obtained and the materials can be forged slowly and welded. Some properties obtained at room temperature taken from the commercial literature are given in Table 2.

Elastic moduli as high as 208 GPa can be obtained with particles of SiC in aluminium. The mechanical properties of these systems will bear a familial relation to those of the "hard metals", cf WC in Co (see for example, Almond (3)). A lot will be learned by application to particulate-reinforced Al alloys of the principles of obtaining toughness, strength and reproducible properties in the hard metals.

Some potential mmcs with putative applications are listed in Table 3.

HIGH TEMPERATURE METAL MATRICES

Figure 1 shows the 1000 rupture strengths of various materials at elevated temperatures. Composites, particularly directionally solidified fibrous composites, figure prominently. The Nitac and Cotac (not shown) series of alloys are characterized by a very regular distribution of apparently unfaulted fibres. Precipitation and solution strengthening is optimized so as to take full advantage of the fibre strengthening due to 13% for Nitac 13, of (Ta + V) C fibres (Rabinovitch et al (4)). The γ-$\gamma'Cr_3C_2$ aligned eutectic is included, because although the high-temperature strength is inferior to that of the Nitac and Cotac series, it overcomes two of the major barriers to the commercial exploitation of *in situ* composites, namely extremely stringent processing conditions and relatively (to current superalloys) poor oxidation and corrosion resistance (McLean et al (5)). If directionally solidified fibre eutectics are to become commercially acceptable it will, according to Meetham (6), be necessary to develop alloys processable under less stringent conditions (as γ-$\gamma'Cr_3C_2$ succeeds) and to accommodate the anisotropy of properties.

TABLE 2. PROPERTIES OF PARTICLE- AND FIBRE-REINFORCED METALS

	E / GPa	σ / MPa	ρ / Mg m^{-3}	E/ρ / 10^4 cm	σ/ρ / 10^4 cm	strain to failure (%)
24 vol. % B_4C in Mg	86	418	1.92 (calc.)	4.4	2.2	0.78
30 vol. % SiC in Al	120	434	2.87	4.2	1.5	3.0
60 % (aligned) Al_2O_3 in Al						
longitudinal	262	690	3.45	7.8	2.0	0.3
transverse	152	185	3.45	4.4	0.53	0.6

E, Young's modulus; σ, yield strength; ρ, density

Table 3

Matrix	Fibre	Potential Applications
Aluminium	Graphite	Satellite, missile and helicopter structures
Magnesium		Space and satellite structures
Lead		Storage battery plates
Copper		Electrical contacts and bearings
Aluminium	Boron	Compressor blades and structural supports
Magnesium		Antenna structures
Titanium		Jet engine fan blades
Aluminium	Borsic	Jet engine fan blades
Titanium		High-temperature structures and fan blades
Aluminium	Alumina	Superconductor restraints in fusion power reactors
Lead		Storage battery plates
Magnesium		Helicopter transmission structures
Aluminium	Silicon carbide	High-temperature structures
Titanium		High-temperature structures
Superalloy		High-temperature engine components
Superalloy	Molybdenum	High-temperature engine components
Superalloy	Tungsten	High-temperature engine components

Figure 1 demonstrates that ceramic materials offer the most promise for extension of service temperature. Graphite at very high temperatures is used as a composite (in reducing atmosphere) as carbon reinforced with carbon fibres. It will be interesting to see whether monolithic ceramics provide adequate properties other than rupture strength; particularly toughness. The ceramic may be carried by a metal in a metal matrix composite or have toughness provided by the incorporation of fibres.

Although nickel base alloys are the most developed for high temperature use, there is much promise in the use of ceramic reinforcement to extend the properties of metals used at lower temperatures then nickel alloys, for example, those based on Ti. A very comprehensive account of continuous silicon carbide fibre reinforced titanium has been given by McElman and Mittrick (13).

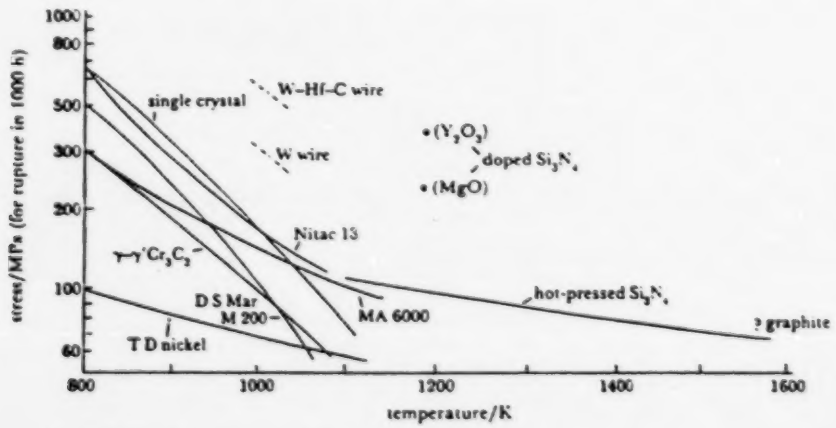

FIGURE 1 1000 h rupture strength of various materials

4. LAMINAR STRUCTURES

There is a rapidly increasing interest in layered microstructures due to (a) the production of epitaxial layers of different composition in the microelectronics industry, leading to quantum-well devices and (b) because vacuum evaporation is one efficient means of evading ingot metallurgy and the restrictions of alloy composition enforced by the conventional phase diagram. Coevaporation of the main alloy constituents is thermally efficient, (Bickerdike (7)) and the method of collection leads directly to a laminated microstructure in a nominally macroscopically homogeneous alloy (for example (6-9 %) Cr-0.6-1.5% Fe-Al (percentages by mass) or else a laminated structure is specifically sought by evaporating layers of different composition for example Al-Ti-Al-Fe. Such layered deposits are not made too slowly for example 18 kg h^{-1} is attained when working on the 0-100 Kg scale.

The high strength of evaporated alloys is derived from the microstructure of the deposits and its further development by working into wrought products. Al-Fe layered microstructures may be heavily rolled and retain the layered microstructure. Within the individual layers there can be a significant contribution to the yield strength from solid solution and dispersion strengthening as well as from dislocation substructure and small grain size: the grain size must be no larger than the layer thickness in one direction and often the grains are equiaxed in three dimensions. With modern techniques uniform layers as thin as one atom diameter may be deposited.

A new type of strengthening - not previously recognised by metallurgists and materials scientists (eg Brown (8)) arises when the thickness of the layers of, say, two pure metals is reduced below 100 nm or so. This was predicted by Koehler (9) and satisfactorily confirmed by Lehoczky (10).

Suppose a specimen is prepared consisting of alternate layers of pure metals (or other materials) A and B. If the elastic constants differ, dislocations will require a large external stress to drive them from the material of lower elastic constant (say A) into that of higher (B). If the layers are thin enough it may not be possible for a Frank-Read source to operate in either layer and then single dislocations will be the mode of plastic deformation. Lehoczky, following Koehler, finds that the tensile stress in the A layers necessary for penetration of the interface is

$$\sigma_a^A = \sigma_m + \sigma_i^A \qquad (1)$$

where $\sigma_m = RG_A/8\pi$ and $R = (G_B-G_A)/(G_B+G_A)$ and σ_i^A is the friction stress in A.

The condition that a Frank-Read source operates in A is

$$\sigma_a^A = 2\alpha G_A b_A/(\tfrac{1}{2}t_A) \qquad (2)$$

In both equations σ_a^A represents the tensile stress in material A due to an applied stress σ_a on the composite, G is the shear modulus (taken to be C_{44}), b the Burger's vector and t the thickness. Setting $\sigma_i^A = 0$, we predict that Koehler strengthening will occur when the right hand side of equation (1) is less than the right hand side of (2) so

$$t \leq \left[32\pi\alpha/R\right] b_A \qquad (3)$$

For an Fe-Al layer structure taking $\alpha = 1$, this predicts that Koehler strengthening will occur when the layer thickness of the aluminium is less than ca. 47 nm. Actually, Bickerdike et al (7) find a large increase in microhardness of Al-Fe deposits at thicknesses less than about 70 nm.

Accurate tensile tests on foils of Al interspersed with either Cu or Ag have been performed by Lehoczky. In Cu-Al foils containing layers of equal thickness the tensile yield stress increases inversely as the first power of the layer thickness down to a value of 70 nm and thereafter remains constant at the remarkably high value, for pure metals, of 650 MPa. The ultimate tensile strength (UTS) of such foils is close to 700 MPa; the tensile fracture stress follows a $t^{-\frac{1}{2}}$ relationship at thicknesses greater than 70 nm. For Al-Ag foils where the difference in elastic moduli is much less than in Al-Cu (R much smaller) the critical thickness for observation of Koehler strengthening is 230 nm and the strength attained is much less.

The Al-Fe system is very interesting because high hardnesses (and presumably high strengths) are obtained with very small Fe layers, for example, 25 nm of Al and 2% by mass)(0.7 vol%) of Fe which corresponds to 1.7 nm layers. Clearly very high values of strength:mass ratio are possible, for example, a layered structure containing 7.3% (by mass) of iron (2.6 vol %) has a tensile strength (closely equal to the yield strength) of 804 MPa and a specific gravity of 2.82 giving a value of σ/ρ 285 MPa: 28.5×10^5cm which is high for an Al alloy.

Such high-strength foils show a stress-strain curve in tension rather like that of fibrous composites even though both phases may be pure metals, particularly when the layer thickness becomes very small, for example 20 nm.

The possibilities are intriguing if one considers other possible combinations of layers, for example Al-Ti, Al-Mg, both of which have been successfully made by evaporation. If means other than evaporation

are considered, perhaps in concert with it, layer structures of Al-C, Al-SiC, Al-B or Al-AlN (or the same non-metal with Mg) become a possibility. The non-metal would appreciably increase the stiffness, the Koehler effect would strengthen the aluminium, and the resistance to crack propagation in the brittle non metal would be increased by the same effect as occurs in laminates where both phases may be considered brittle.

By direct measurement Lehoczky found an apparent increase in the Young modulus of his Al-Cu foils at thicknesses of the layers of less than about 50 nm. Though the measurements indicate an increased stiffness, whether or not there is a genuine increase in Young's modulus in foils containing thin layers is a very intriguing question at the present time. It has usually been assumed that Young's modulus of a pure pore-free solid cannot be greatly changed except by feeding in energy, for example, in piezoelectric materials. Hilliard and his co-workers at Northwestern University have reported a number of times (see, for example, Baral et al (11)) observing very large increases in the measured stiffness of foils containing layers less than 3 nm thick. The foils are single crystals and of course account must be taken of the crystalline anisotropy. A very large increase in the Young modulus in the plane of the foil is found in Ag-Pd, Cu-Ni, Au-Ni and Cu-Pd but not in Cu-Au (Henein & Hilliard (12)) when there is marked compositional modulation normal to the plane of the foil with a wavelength of 2.0-3.0 nm. The effect disappears at longer wavelengths and at very short ones and is according to these authors very large, for example, by a factor of 2-3. Theoreticians have sought explanations for a genuine increase in the Young modulus in terms of Fermi-surface-Brillouin-zone interactions.

Were the effect found to be real it would be of extreme interest for structural materials, particularly for Al-base layer structures such as Al-Fe mentioned above, because the possibility arises of varying and controlling both strength and stiffness by varying layer thickness.

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REAL COMPONENTS IN MMCS

A note by A Kelly

The following summarises work on some actual components made in MMCs in the aircraft industry and the automotive industry. The components described for use in aircraft are based on a report by M J Ball of the British Aerospace Civil Aircraft Division.

1. Introduction

Metal matrix composites (MMCs) have considerable potential for providing light weight components exhibiting high strength, high stiffness, good wear resistance and excellent elevated temperature properties compared to the matrix alloy. Consequently they are applicable to both aircraft, missile, space and engine manufacture. A fibre reinforced aluminium composite can exhibit strengths in excess of 1,400 MPa and a modulus of 210 GPa while a typical particulate can have a modulus of 120 GPa both with densities approximately equivalent to the aluminium matrix alloy. For comparison a typical 2,000 series aluminium alloy would exhibit a tensile strength of 483 MPa and a modulus of 72.4 GPa.

Currently the cost of MMCs preclude them from achieving their immediate potential. During the past few years development activities in the USA, Japan and Europe indicate that major price reductions are envisaged. It has been shown that price is related to usage and therefore as the applications steadily increase the price is expected to fall. Present fibre prices, for example, are considerably lower in real terms than in the early 1970s and since 1980 the cost of silicon carbide fibre has halved.

The USA Aerospace industry is continuing a high level of research activities with MMCs which started in the late 1970s. The Munitions List restrictions on information still makes it difficult to obtain much information on these programmes or the future applications. However, companies such as AVCO Specialty Material Division has increased the capacity of their silicon carbide fibre manufacturing facility and DACC (Alcan) and DWA are currently planning major increases in their production capacity.

It seems likely that the main US aerospace manufacturers will incorporate MMCs into their products. The Lockheed "Structural Demonstration Programme" has a primary objective to design, manufacture and test four vertical tail structures and establish a property data base by the end of 1988. The successful completion may then enable MMCs to be specified for the Advanced Tactical Fighter.

MMC activities in Europe have increased significantly during the past year or so. Aerospatiale are reported to be the largest purchasers of MMCs outside the USA. All of the engine manufacturers have active programmes mainly working with titanium base MMCs. Perhaps the most accurate measurement of the application potential for MMC is through the investment by potential suppliers such as Alcan.

The Japanese MMC programmes have increased signficantly during the past few years. They have a capability to supply a wide range of various reinforcements particularly with continuous fibre tows and discontinuous whiskers. The VMC Company of Japan is developing a competitive silicon carbide fibre to AVCO.

During 1985 the report of the Materials Advisory Group (the Collyear Committee) in the UK - A Programme for the Wider Application of New and Improved Materials and Processes (NIMP) - emphasised that MMCs will have impact on; all transport industries including aerospace, industrial machining manufacturers, diesel engine manufacturers, component industries and material suppliers. It emphasised that the aerospace industry is keen to exploit a manufacturing process technology. The report also drew attention to USA restrictions on information and the Japanese interests and concluded that "it is vital that the UK develop a capability in this area".

2. Metal Matrix Composite Types

MMCs can be characterised by the method of reinforcement ie Continuous Reinforcement and Discontinuous Reinforcement, and each can be further divided - Table 1.

	Type	Materials
Continuous Reinforcement	Monofilament	Boron Silicon Carbide
	Multifilament (Tow or Yarn)	Carbon Silicon Carbide Alumina
Discontinuous Reinforcement	Particulate	Silicon Carbide Boron Carbide
	Whisker	Silicon Carbide Silicon Nitride Carbon
	Short Fibre	Alumina

Table 1 - MMC TYPES

This is not an exhaustive list of all MMCs but restricted to those reinforcements of current practical interest to the aerospace and automotive industry.

Monofilaments are relatively large diameter fibres (100-200 μm). They are produced by chemical or physical vapour deposition techniques which involve coating a substrate core of either tungsten or of carbon with boron or silicon carbide. Multifilament yarn consists of small diameter filaments (5-20 μm) with typically 500-1,000 filaments per yarn. Table 2 compares the basic properties of both types of continuous reinforcements.

Fibre Type	Composition	Mean Diameter um	Failure Strength MPa	Modulus GPa	Density Mg/m^3
Mono-filament	Boron	140	3,600	400	2.57
	Silicon Carbide	140	3,400	400	5.00
Multi-filament	Carbon	7 6.5	3,500 2,700	230 390	1.76 1.81
	Silicon Carbide	8-15	2,800	200	2.3-2.6
	Alumina	17	1,800	210	3.25

TABLE 2 - BASIC PROPERTY COMPARISON OF CONTINUOUS REINFORCEMENTS FOR MMCs

MMCs containing monofilaments can be produced by either solid state or liquid infiltration techniques. The solid state processes basically involve sandwiching the fibres between foil or combinations of foil and powder and diffusion bonding. The resultant MMC can be in the form of a single-ply sheet, multiply sheet/plate or a structural shape. Liquid infiltration involves preplacing fibres and using various casting techniques to achieve a near net shape part. Multifilament yarns by nature are not suitable for solid state processes and consequently liquid infiltration is used to produce the MMC. The yarn can be woven into a preform which is the subsequently liquid metal infiltrated.

Particulate reinforcement is generally silicon carbide supplied in a flake or angular form with an approximate maximum dimension of 3-15 μm. Similarly, most whiskers used for MMCs are silicon carbide and have an average diameter less than 1 μm with a length of 50-200 μms. The methods for manufacturing an MMC from both of these types of reinforcement involves either producing a near net shape part or producing a billet which is processed into a shape using conventional metal working technology, ie rolling, forging, extrusion. There are several ways of manufacturing a part or billet. The powder metallurgy procedure involves mixing powder metal with the particulate or whisker and sintering to produce the required end form. Liquid metal processes applied to particulate involve obtaining a good distribution of particles through a melt and casting using conventional techniques to produce a part or billet. With whisker it is necessary to produce a preform and liquid infiltrate. A further method of producing particulate MMCs involves a metal spraying process. Molten aluminium is sprayed onto a mould. The particulate is injected into the spray so that the composition of the billet is uniform.

Short fibre MMCs are of little interest to the aerospace industry, particularly in comparison to other discontinuous reinforced material. The main interest has been to extend the elevated temperature properties of aluminium for such applications as diesel engine piston crowns. The principal short fibre material is alumina and was primarily developed for furnace insulation. A typical fibre has a mean diameter of 2-5 μm and a length of 200 mm. Liquid infiltration of fibre preform is used to produce a MMC.

3. MMC Development at British Aerospace (M J Ball)

The Civil Aircraft Division of British Aerospace plc at Bristol has been involved with the development and evaluation of MMCs for several years. The overall objective of the project is to develop low cost manufacturing techniques and demonstrate the potential of MMCs by applying these techniques to the design, manufacture and test of representative structures.

Although some work has been carried out on titanium matrix composites, virtually all of the development activities have been with aluminium alloy base MMCs. The first phase of this project has now been completed and a British Aerospace developed manufacturing technique scaled-up to enable representative structures to be successfully produced.

The basic manufacturing technique for producing MMC parts by low pressure diffusion bonding methods was developed by British Aerospace in 1981 and enables diffusion bonding of

aluminium at low pressures (less than 7 MPa). The process has been applied to the bonding of monotapes (single plies) of fibre reinforced aluminium. This involves a lay-up and bonding process analogous to non-metallic composite part manufacture. Multi-ply sheet and various structural shapes such as "Z", "I", Hat and Channel sections have been made from low pressure bonded monotape. The microstructures indicate little or no evidence of the original interfaces between plies.

The British Aerospace programmes have also involved assessing the basic mechanical properties of MMCs, including continuous fibre reinforced material manufactured by British Aerospace and both continuous and discontinuous reinforced MMCs produced by various other companies. The continuous fibre reinforced MMCs evaluated included boron, coated boron and silicon carbide reinforced aluminium. The principal source of monofilament reinforced MMC has been the USA and the source for multifilament has been Japan. Both powder metallurgy, cast and sprayed particulate have been evaluated from both USA and UK sources. Table 3 indicates the basic mechanical properties of some of the continuous fibre reinforced MMCs evaluated.

Material	Type	UTS (MPa)	Modulus (GPs)	Density (g/cm^3)
Boron/ Aluminium	Monofilament	1,450	220	2.66
SiC/ Aluminium	Monofilament	1,600	220	2.71
SiC/ Aluminium	Multifilament (Tow)	1,200	120	2.70
Alumina/ Aluminium	Multifilament (Tow)	860	150	2.90
SiC/ Magnesium	Monofilament	1,500	210	2.20

Fibre Volume Fraction 45-50%

TABLE 3 - BASIC MECHANICAL PROPERTIES OF UNIDIRECTIONAL CONTINUOUS FIBRE REINFORCED MMC'S

Table 4 indicates some of the basic mechanical properties of particulate and whisker reinforced MMCs with 2000, 6000 and 7000 series aluminium alloy matrices.

Matrix	Reinforcement Volume Fraction	Yield Strength (MPa)	UTS (MPa)	Modulus (GPa)
6061	20% SiCp	414	496	104
6061	40% SiCp	448	586	145
2124	20% SiCp	400	551	104
2124	40% SiCp	517	689	152
7090	20% SiCp	655	724	104
7090	40% SiCp	689	710	145
6061	17% SiCw	-	530	110
2014	17% SiCw	-	680	-
7270	17% SiCw	-	880	-

SiCp - Particulate, SiCw - Whisker

TABLE 4 - BASIC MECHANICAL PROPERTIES OF PARTICULATE AND WHISKER REINFORCED MMC'S

Other mechanical property assessments have included compression, fracture toughness and fatigue testing. In addition testing of various fibre orientations has been carried out which has included bearing tests. The main features of MMCs resulting from these tests are as follows:

(a) Continuous Fibre Reinforced MMCs - Unidirectional testing indicates very high specific strength and stiffness. Fracture toughness and fatigue are also very high. However, transverse tensile properties are very low particularly with respect to strain to failure. Recent developments by AVCO in conjunction with Lockheed have reportedly increased transverse strain four-fold. Crossplied MMCs have exhibited predicted properties.

(b) Particulate or Whisker Reinforced MMCs - Isotropic properties with strength similar to the matrix alloy but modulus increased signficantly and proportioned to the volume fraction. Fatigue strength is approximately equivalent to the matrix alloy. Ductility is low with values of around 1% with 7000 series and high volume fraction. However, values of approximately 5% are achieved with a 2000 series matrix and lower volume fractions. Fracture toughness testing at British Aerospace has given values of K_{1c} approximately 20 MPa $\sqrt{m}$. However, the manufacturers are claiming that,with improved material, values of approximately 30 MPa $\sqrt{m}$ are currently being achieved. A tough aluminium alloy of high strength without reinforcement would show values of K_{1c} of 20-40 MPa $\sqrt{m}$.

The principal objective of the British Aerospace programme was to design, manufacture and test representative structures. This has involved compression testing of various elements to assist in establishing a design criteria. Subsequently large compression panels representing both fuselage and wing sections were manufactured. The panels consisted of particulate MMC skins and continuous fibre reinforced "Z" section struts. The panels were compression tested and either met or exceeded the design predicted failure loads.

During the past few years design studies have been carried out to identify potential structural applications for MMCs. Results from both mechanical property and structural tests have assisted with these studies. A wide range of potential Civil Aircraft applications have been identified including both skin and structural members. These studies indicate that substantial quantities of MMCs could be used providing the costs are competitive and the following rough order of magnitude of target costs have been established.

(a) Particulate or Whisker MMC - Competitive with Aluminium Lithium Alloys

(b) Continuous Fibre MMC - Competitive with Carbon Fibre/Epoxy (Laminated)

(c) Continuous Fibre MMC - Competitive with existing forged (Liquid Infiltrated and machined titanium and high near net shape) cost steel components

Based upon predictions by various material suppliers there would seem to be no reason why these costs cannot be achieved or in fact improved on. Typical Civil Aircraft applications with weight savings ranging from 20-60% include the central section of a fuselage, floor beam struts, keel longeron tubes and a complete wing section.

4. The needs

The potential offered by MMCs for significant weight savings in aerospace structures is significant. If the predicted costs of MMCs are achieved these advanced materials will find numerous applications. The considerable worldwide investment being made by the material supply industry and the intensive activities within the US aerospace industry indicate the likelihood of MMCs being used in the next generation of civil and military aircraft. For the UK and European aerospace industry to ensure its competitiveness. The following are thought to be the requirements:-

1. Manufacturing - This requires developing a basic cost effective manufacturing technology within the UK and Europe as recommended by the Collyear Committee and currently being tackled by the Civil Aircraft Division of

British Aerospace at Bristol. The ability to apply conventional metal working techniques such as machining, drilling, forming and joining etc, are assessed as an essential element of manufacturing technology.

2. Properties - Establish a mechanical property data base. Solving some fundamental problems such as the poor fracture toughness of particulates and the low transverse strain of, for example, silicon carbide fibre reinforced aluminium.

3. Design - Develop design techniques and structural analysis methods.

4. Education and Training - The opportunities offered by MMCs and other similar new and improved materials and processes will require more engineers and scientists with broad backgrounds in these fields. There is also a great need for continuing education/training for designers and engineers in industry who are unfamiliar with these new materials. In addition it is also necessary to create an awareness of new material technologies as these materials may rapidly become commonplace.

5. In Service Behaviour - Determine environmental effects including corrosion resistance and impact/damage tolerance. In addition there will be a need to establish a repair capability.

6. Project Management - MMCs similarly to some other new and improved materials and processes cut across established disciplines and multi-disciplinary teams may be required.

Potential Automotive Applications

The requirements to achieve use of MMCs in the automotive industry are similar to those in the civil aircraft industry with the cost of the material being of even greater import. Striking figures are as follows:

	Volume Motor car	Airbus 300	Ariane 2
Price of Vehicle (10^3\$)	10	60,000	50,000
Weight of Vehicle (Kg)	850	83,000	30,000
Price/Kg	12	720	1650

TABLE 5

MMCs offer weight reduction, metal to metal compatability, enhanced temperature capability and tailored properties for specific components. The specific property benefits are increased elastic modulus and tensile strength, better fatigue resistance (but not for particulates) better wear and thermal resistance and reduced coefficient of thermal expansion.

The potential automotive applications which have been realised as components are: piston crowns (already referred to), connecting rods, gudgeon pins, cylinder liners and components of valve gear and braking systems.

The barriers to implementation are first and foremost the high material costs. There is little if any acceptance of cost penalty for material substitution in the volume car industry whereas for a helicopter up to $250 per Kg saved would be accepted and up to $650/Kg for an earth satellite. Other problems are the absence of a materials data base and of consistent fabrication methods so that the needs are:

- cheaper reinforcement
- volume production
- data bases
- elimination of batch-batch variations and process control
- near/nett forming processes and scrap recycling capability development of appropriate test methods.